Computational Fluid Dynamics Demonstration of Rigid Bodies in Motion

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The Design Analysis Brach (NE-M1) at the Kennedy Space Center has not had the ability to accurately couple Rigid Body Dynamics (RBD) and Computational Fluid Dynamics (CFD). OVERFLOW-D is a flow solver that has been developed by NASA to have the capability to analyze and simulate dynamic motions with up to six Degrees of Freedom (6-DOF). Two simulations were prepared over the course of the internship to demonstrate 6-DOF motion of rigid bodies under aerodynamic loading. The geometries in the simulations were based on a conceptual Space Launch System (SLS). The first simulation that was prepared and computed was the motion of a Solid Rocket Booster (SRB) as it separates from its core stage. To reduce computational time during the development of the simulation, only half of the physical domain with respect to the symmetry plane was simulated. Then a full solution was prepared and computed. The second simulation was a model of the SLS as it departs from a launch pad under a 20 knot crosswind. This simulation was reduced to Two Dimensions (2D) to reduce both preparation and computation time. By allowing 2-DOF for translations and 1-DOF for rotation, the simulation predicted unrealistic rotation. The simulation was then constrained to only allow translations.

Nomenclature

deg, °	=	Degree
F_x, F_y, F_z	=	Resultant force components applied at CM in x, y, and z directions respectively, lb_f
h	=	Height from sea-level, ft
I_{xx}, I_{yy}, I_{zz}	=	Moments of inertia about the x, y, and z axis respectively, slug · ft^2
I_{xy}, I_{yz}, I_{zx}	=	Products of inertia about the x, y, and z axis respectively, slug · ft^2
m	=	mass, slug
M_y	=	Y component of resultant moment applied at CM, lb_f · ft
M_∞	=	Freestream Mach number
NE-M1	=	Engineering and Technology Directorate-Mechanical Division-Design and Analysis Branch
q_∞	=	Freestream dynamic pressure, psf
Re_∞	=	Freestream Reynolds number, 1/ft (per foot)
s	=	Second
T_∞	=	Freestream temperature, °R
V_∞	=	Freestream velocity, ft/s
α	=	Angle-of-attack, deg
β	=	Angle-of-sideslip, deg
γ	=	Flight path angle, deg
μ_∞	=	Freestream dynamic viscosity, lb · s /ft^2
Δt	=	Time step, s

Acronyms

CFD	=	Computational fluid dynamics
CGT	=	Chimera Grid Tools

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CM = Center of Mass
DOF = Degrees of freedom
GUI = Graphical User Interface
LCC = Launch Commit Criteria
LPVD = Launch Pad Vehicle Drift
NASA = National Aeronautics and Space Administration
RBD = Rigid Body Dynamics
SLS = Space Launch System
SRB = Solid Rocket Booster
2D/3D = Two dimensional/three dimensional
XML = Extensible Markup Language

I. Introduction

THE Engineering Design Analysis Branch (NE-M1) in the Mechanical division of the Engineering and Technology Directorate at the National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC) has never had the ability to couple rigid body dynamics (RBD) and computational fluid dynamics (CFD). Technical management within NE-M1 can identify several analyses that may benefit by coupling dynamic motion and CFD. The requirements of this project were to demonstrate to NE-M1 the capability of analyzing moving bodies subjected to aerodynamic loads.

With the growing possibility of the new Space Launch System (SLS), NE-M1 expects a great deal of analysis work in the future that corresponds to the SLS. Thus two different moving body simulations were developed based on geometry derived from a conceptual SLS that is being considered. Figure 1 shows the geometry of a possible SLS configuration. The first study modeled was the RBD of a Solid Rocket Booster (SRB) during its ejection from the core stage. The second was a simulation of the SLS as it departs from a launch pad under the influence of a crosswind. The outcome of the two simulations in this project was to demonstrate to technical management in NE-M1 that CFD can be coupled to RBD.

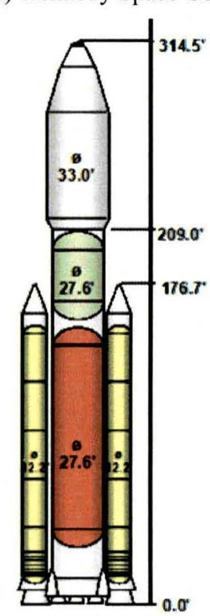


Figure 1. Possible SLS configuration. The diameters and lengths used to construct the grids for SLS concept vehicle.

OVERFLOW[1] is the name of the software that was chosen to demonstrate moving body capability. OVERFLOW is a flow solver that was developed by NASA and is non-commercial. Thus, the code is readily available within NASA. Since OVERFLOW makes use of *overset* structured grids to compute fluid flow around geometries, a description and nomenclature of the overset gridding method will be discussed.

The overset or *Chimera* grid method is a discretization technique that allows a physical domain to be decomposed into multiple overlapping grids. OVERFLOW was designed to make use of overset structured grids and thus any subsequent reference to *grid* will refer to such grids. Chimera Grid Tools[2] (CGT) is the software that was developed by NASA Ames and was the software used in this project to construct all grids.

II. Geometry Descriptions and Modeling

The dimensions of the SLS that was modeled for both the SRB separation and the launch pad vehicle drift (LPVD) simulations were derived from figure 1. Only lengths and diameters were provided and thus, specific contours of the payload faring and nose cones were approximated to aesthetically represent figure 1. Since the purpose of the simulations presented here was to demonstrate the capability of RBD coupled to CFD, the exact geometry was not crucial.

As a preliminary demonstration of CFD and RBD, major simplifications were made to the model. In this project, rocket plumes, nozzles, and attach hardware were not included and thus any phenomena caused by these elements were not represented.

Table 1 is a summary of fight conditions for the SRB separation and the LPVD simulations respectively. The flight conditions for the SRB separation case were derived from references 3 and 4. For the LPVD simulation, the

flight conditions were chosen such that the most unfavorable wind conditions that could occur for the SLS would be modeled at sea level. Based on a Launch Commit Criteria (LCC) for wind, a crosswind of 20 knots was simulated.

	SRB Separation	LPVD
h	173,857	0
V_∞	4,112	33.76
M_∞	3.877	0.0302
q_∞	12.83	1.35
μ_∞	3.4×10^{-7}	3.39×10^{-7}
Re_∞	18,370.77	141,000
T_∞	468.2	518.7
α	3.0	--
γ	36.966	--

Table 1. Initial flight conditions used for the SRB separations simulation and LPVD simulations.

A. Geometric Modeling of SRB Separation Simulation

Feature curves were identified as the first step in generating a geometric model of the core stage and SRB. Since CGT reads files in *PLOT3D* format, a simple text file was created that contained the information for a single point located at the origin. This file was named *origin.dat* and details for this file are in the appendix *A* (figure A1). Once *origin.dat* was created, the file was opened in CGT's Graphical User Interface (GUI) named *OVERGRID*. There was a *read append* feature in OVERGRID that allowed additional files to be appended to the current OVERGRID session. Thus, the file *origin.dat* was appended several times and each appended point was then translated from the origin to locations where there were geometric discontinuities in the rocket's geometry. Since the core and booster were axisymmetric bodies, one feature curve was needed to create the core and SRB respectively. Figure 2 is an illustration of the surface grid generation process employed to create the surface grid for the core stage. A similar process was used to create the SRB surface grid.

Due to NE-M1 unfamiliarity with the OVERFLOW software and its dynamic mode, a half-configuration of the SRB simulation was first created to experiment with parameters such as applied forces and moments, and time-steps. A full simulation that included both SRBs was constructed after the correct OVERFLOW files were created.

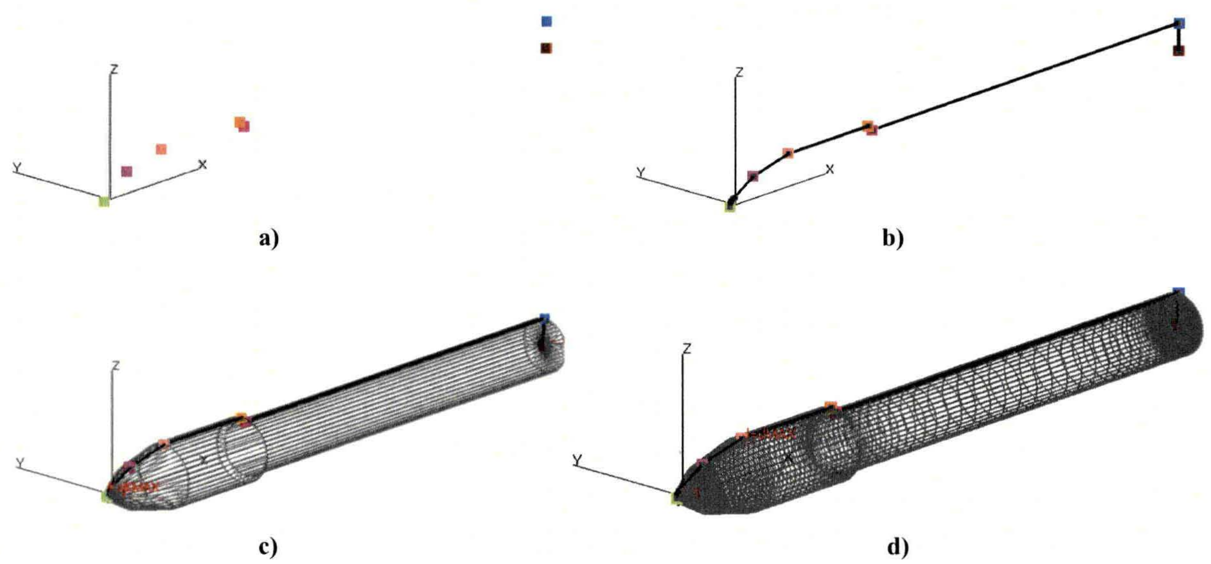


Figure 2. The surface grid generation process of the core stage in CGT: a) Feature points. b) Feature curve. c) Feature curve revolved about x-axis. d) Points added and redistributed on surface.

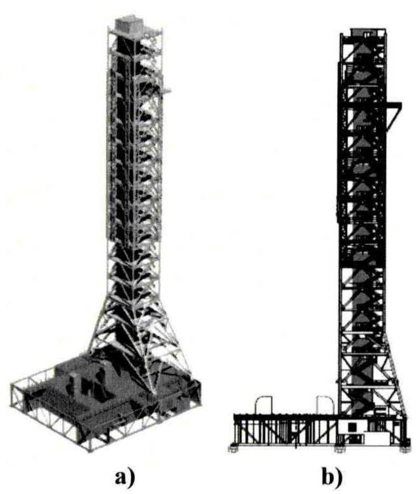
B. Geometric Modeling of Launch Pad Vehicle Drift Simulation

Since the project was intended for demonstrational purposes, a decision was considered to make LPVD simulation two dimensional (2D). The launch pad that was modeled was derived from a mobile launch platform that was designed for two SRBs and three RS-25E rocket engines. Figure 3(a) illustrates an isometric view of the launch pad and figure 3(b) shows the 2D view of the launch pad as was desired for modeling.

For the CFD model of the launch pad, only the bulk dimensions, such as the total heights and widths were implemented. The intricacies of the truss structure were not represented in the CFD model. Moreover, the CFD model of the launch pad does not allow air to flow through the tower as it actually does.

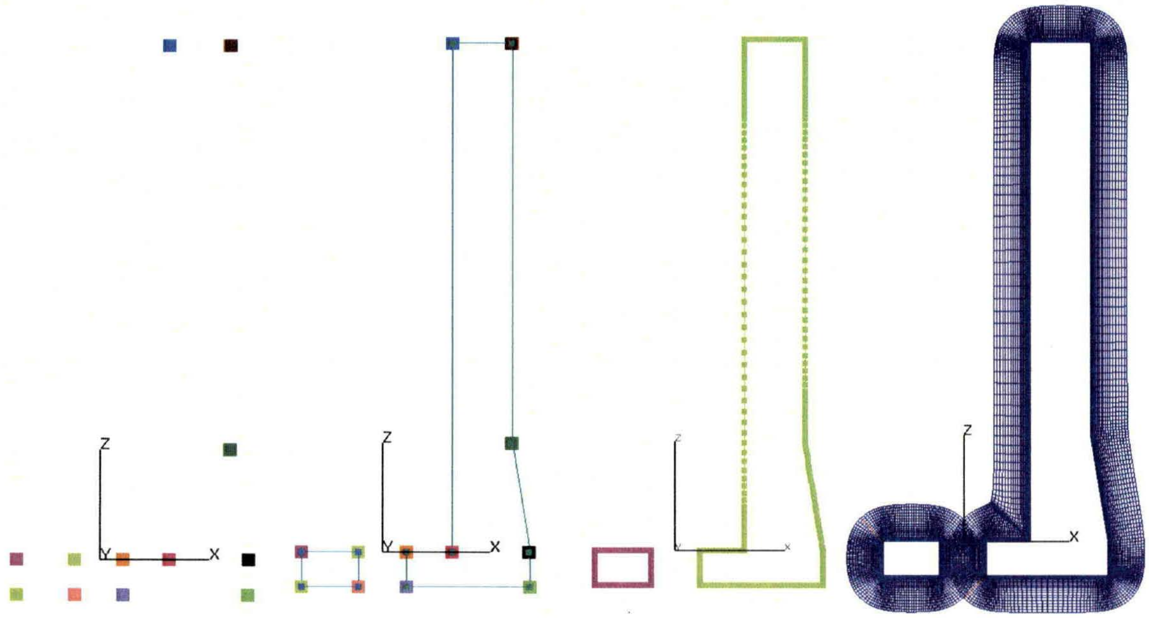
Since our proposes were to model the SLS under the least favorable wind conditions and due to the way the launch pad was designed to hold the launch vehicle, reducing the problem to two dimensions required the removal of the SLS's SRBs from the CFD model. The least favorable wind condition would be a twenty knot crosswind that causes the launch vehicle to drift toward the tower.

The geometry for the pad was created in OVERGRID in a similar manner as the geometry from the SRB separation simulation. Instead of using the *origin.dat* file that was created for the SRB separation simulation, a new PLOT3D formatted file was created and it was named *12pts.dat.* This file contained the twelve points needed to represent every corner of the launch pad model. See the appendix *A* to view the contents of *12pts.dat*. Figure 4 outlines the grid generation process for the launch pad. Note the x, y, and z coordinate directions in Figure 4(d). On the other hand, the geometry of the core was derived from the same grids that were developed for core stage in the SRB separation simulation. As shown in figure 5(b), the first and last grid planes were extracted from the volume grid of the core. Then those two planes were concatenated to form a single grid as shown in figure 5(c). Finally, the grid was translated and rotated to *sit* on the launch pad grids as shown in figure 5(d). Note that the origin is on the centerline of the core stage and at the top surface of the launch pad.



a) b)

Figure 3. The launch pad that was modeled for the LPVD simulation. (a) Isometric view of launch pad. b) 2D view of tower for CFD model.



a) b) c) d)

Figure 4. The grid generation process for the launch pad CFD model as viewed in OVERGRID. a) Points in PLOT3D file named *12pts.dat*. b) Two feature curves created from concatenating points together. c) Points added between initial points for finer grid spacing. d) Resulting near-body grids for launch pad.

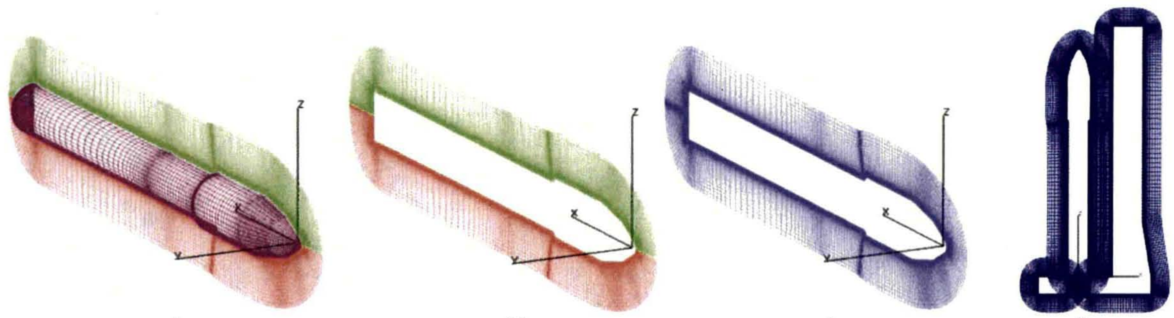


Figure 5. Grid generation process for the core stage of the 2D LPVD case. a) Near-body volume grid generated for the 3D SRB separation case. b) First and last grid planes extracted. c) Concatenated grid planes to form near-body volume grid. d) Near-body grid rotated, translated, and read into launch pad grid file.

III. Requirements for Simulations in OVERFLOW Mode-D with Grid Movement

OVERFLOW makes use of *Mode-D* to enable grid movement; also known as OVERFLOW-D. This section will summarize the OVERFLOW-D input requirements and the procedures needed for both the SRB separation and LPVD simulations. Typically a new directory (referred to as *working directory* in this report) was created that would contain all of the required input files for each simulation case.

A. Near-Body Grids Represent Solid Geometry

OVERFLOW-D only requires the near-body grids of a problem to simulate RBD. Thus, a PLOT3D file named *grid.in* that contains the near-body grids for a particular simulation was required in the working directory.

As previously mentioned, both a full- and half-configuration model was setup for the SRB separation simulation. Thus the *grid.in* for the half-configuration contained half of the core stage and a single SRB. The *grid.in* for the full case contained the full volume grid for the core-stage and two SRB near-body grids. Due to the ability to translate (and rotate) grids to other locations in the XML files, both volume grids for each SRB was placed in the same coordinate location. See the XML file section below.

The *grid.in* for the LPVD simulation contained the near-body grids for the two launch pad components and the core. Note that since this case was 2D, OVERFLOW required a total of three grid planes to be supplied. Thus the *GRIDED* utility (batch mode) in CGT was used to add a plane in front and behind the original plane that was located at y = 0. The two additional grid planes supplied had to be located at y = 1 and y = - 1 respectively. Figure 6 shows the graphical contents the *grid.in* file for the 2D LPVD and highlights the three planes needed.

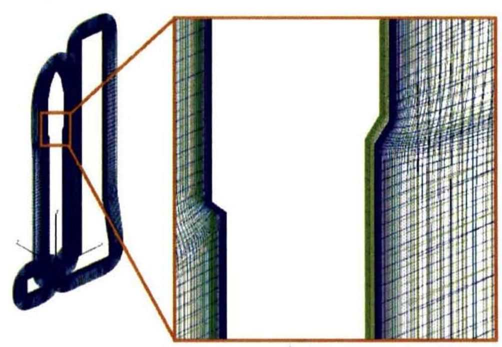


Figure 6. Illustration of the three planes needed for a 2D simulation in OVERFLOW.

B. Force and Moment Coefficient Pre-Processor

MIXSUR is a CGT utility that was needed to generate input files that OVERFLOW-D utilized to compute the force and moment coefficients at each computational iteration. *grid.in* had to be in same directory as the directory that ran MIXSUR so that an integration surface could be generated. A file named *mixsur.inp* was needed for each simulation. Reference 5 was frequently consulted during the generation of the each *mixsur.inp* file. The same *mixsur.inp* that was created for the 3-DOF LPVD case was reused for the 2-DOF case. For the SRB separation simulations, one *mixsur.inp* was needed for the half-configuration. For the full-configuration case, the same *mixsur.inp* for the half-configuration case was modified to include the second SRB. See the appendix for the *mixsur.inp* files created for each case.

One of the many files that were generated after running the MIXSUR utility is *grid.i.tri.* For each simulation, this file was opened in the OVERGRID GUI and visually inspected before running OVERFLOW. Figure 7 is the *grid.i.tri* file that was generated for the half-configuration SRB separation case.

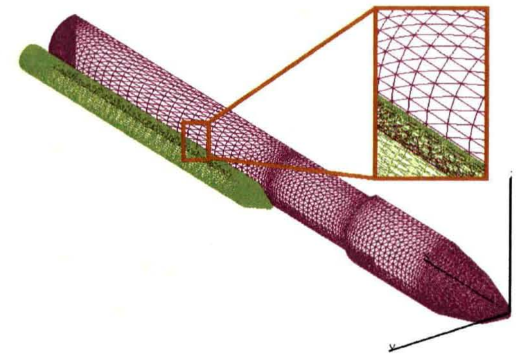


Figure 7. Force and moment integration surface for the half-configuration SRB separation simulation that was created by the CGT utility named MIXSUR.

C. OVERFLOW Input File

For every simulation, OVERFLOW read a text file that contained all of the CFD input variables. The default name was *over.namelist* or *overflow.inp.* Different input files were distinguished by naming the files of the form *overflow.*.inp* where * denotes text that distinguished one input file from another. This naming convention was very useful when a few changes, such as angle-of-attack and freestream Mach number were made, and also when a shell script was created to automate running multiple cases.

The OVERGRID GUI in CGT allowed the *overflow.inp* file to be generated by interactively selecting the OVERFLOW flow solver input options. After an OVERFLOW input file was generated by OVERGRID, it was often the case that several parameters needed to be experimented with.

D. Configuration and Scenario XML Files in OVERFLOW Mode-D

There are three ways in OVERFLOW-D to specify dynamic grid motion[1]. The method chosen for this project was to set dynamical parameters in Extensible Markup Language (XML) files that use the Geometry Manipulation Protocol[6] (GMP). For each computation in OVERFLOW-D, the XML files named *Config.xml* and *Scenario.xml* had to be present in each working directory. For details of the contents in the XML files, refer to chapter 5 of reference 1 and for the XML files made for each simulation in this project see appendix B, C, and D.

	Dimensional	Non-Dimensionalized by V_{ref}
I_{xx}	217,308	143,191,840,543
I_{yy}	11,405,920	7,510,971,307,750
I_{zz}	11,408,799	7,522,448,851,710
I_{xy}	-1,636	-1,078,034,995
I_{yz}	8,589	5,659,683,726
I_{zx}	-177	-116,962,843
m	181,357	3,776,357,525
F_x	410,560	16,000
F_y	±513,200	±20,000
M_z	±2,566,000	±100,000

Table 2. Inertial parameters used in the SRB separation simulation.

Grouping grid numbers to a component and any translations or rotations were contained in the *Config.xml* file. The *Scenario.xml* had the ability to specify inertial properties, aerodynamic 6-DOF, forces and moments, motion constraints, and any additional translations or rotations. Table 2 summarizes the inertial parameters used for the SRB in SRB separation simulations. Note that the F_y and M_z values in table 2 were positive or negative according to which SRB the load was being applied to. See chapter 5 of reference 1 for a list of equations that non-dimensionalize the dynamics quantities by the reference velocity. As a final comment for the non-dimensional values in table 2, the reference velocity used for all SRB separation simulations was 4,112 ft/s. The reference velocity chosen was the relative ground velocity that was stated in reference 4 however, the relative wind velocity of 4,106 ft/s in reference 3 should have been used instead. The OVERGRID GUI was used to assist in the construction of each XML file.

	Dimensional	Non-Dimensionalized by V_{ref}
I_{yy}	16,660	7×10^7
I_{xy}	0.0	0.0
I_{yz}	0.0	0.0
m	178,992	7.53×10^7
F_z	8,407,990	3.1×10^6

Table 3. Inertial parameters used in the LPVD simulation.

Table 3 lists the inertial properties and their non-dimensionalized values that were input into the *Scenario.xml* file for the LPVD simulation. F_z was a constant value that simulated the thrust that the launch vehicle would produce and was calculated by assuming a thrust to weight ratio of 1.46. The reference velocity was determined from the Mach number that would represent a 20 knot wind velocity and the speed of sound in air at sea level.

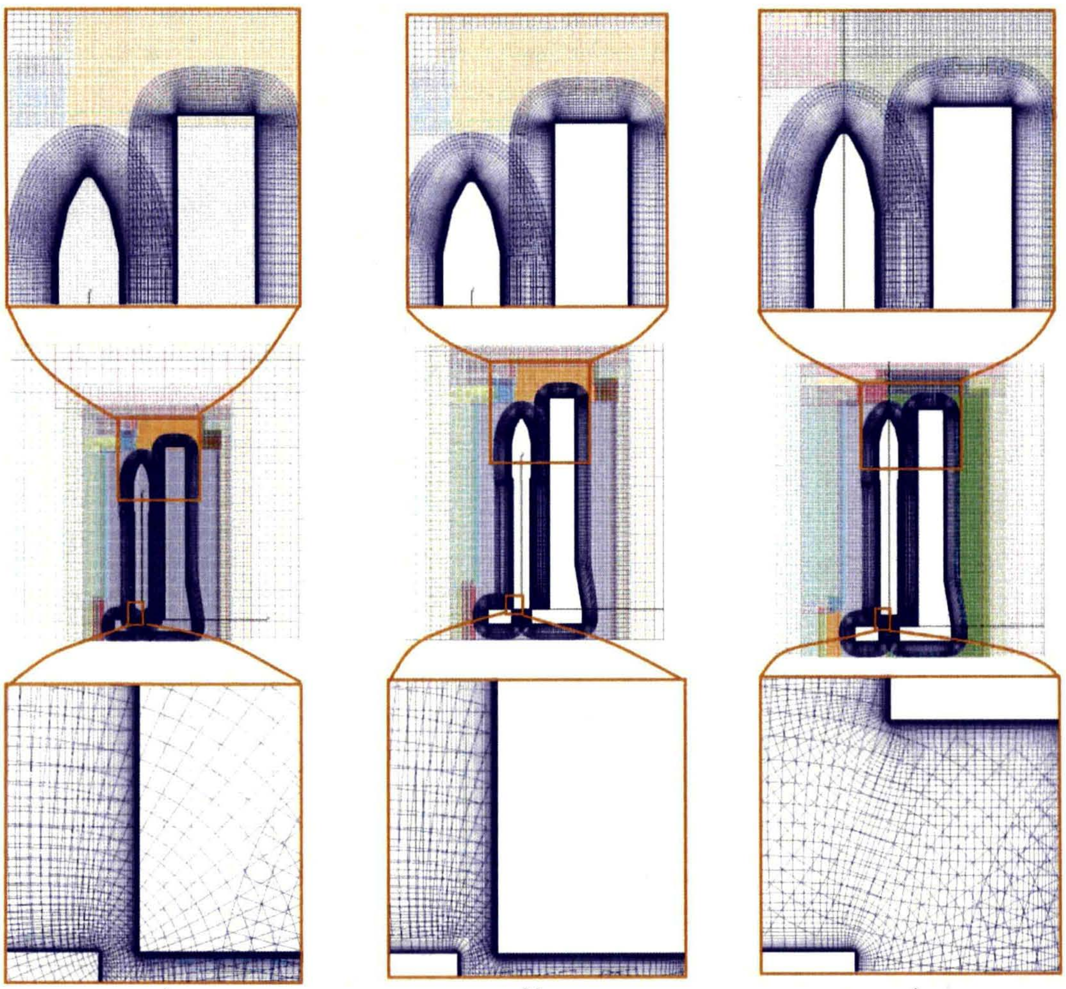
E. Object X-rays in OVERFLOW D-Mode and their Function

Hole-cutting is a standard procedure that is needed in Chimera grid systems. Hole-cutting is the name of the procedure for blanking-out grid points. As several grids are overlapped, some grids may have points that are defined within solid geometry; such points must be removed or *blanked-out* of the computational domain. Figure 8 is an illustration of hole-cutting before and after the hole-cutting procedure and after grid motion has occurred. OVERFLOW-D has a built-in hole-cutter.

The method in which holes were cut in OVERFLOW-D was by supplying *object X-rays*[7]. The X-rays that were required for both simulations were created in OVERGRID and the filename had to be named *xrays.in*.

A CGT utility named *XRAYED* was a very noteworthy tool in the process of creating a moving-body simulation in OVERFLOW-D. Each near-body grid that defined a hole-cutter needed an X-ray and each X-ray had a *component ID*. The *component ID* was an integer that had to match the n^{th} component defined in the *Config.xml* file[1]. It was crucial that the *component ID* matched the order of the defined components in the *Config.xml* file. For example, if the *component ID* of the third defined component in a *Config.xml* file is not equal to 3, then, if and when the grid(s) of the third component moves under the influence of dynamic motion, then the X-ray will not move with it; thus, the hole-cutting will be ineffective. Therefore, XRAYED was needed during the problem-stepup phase of each simulation to make sure that the *component IDs* of each X-ray were properly numbered.

For the half-configuration SRB separation case, two X-rays were required; one for the core and one for the booster. For the full-configuration of the SRB separation case, XRAYED was used to duplicate the X-ray that was already defined for the booster in the half-configuration case and a new X-ray was needed for the core. For the LPVD case, one X-ray was used for the near-body grid of the core, and, since both near-body grids for the launch pad would remain fixed, one X-ray was used for both launch pad grids.



a) b) c)

Figure 8. Hole-cutting required for the LPVD simulation. a) Before hole-cutting procedure. b) After hole-cutting procedure. c) Hole-cut after near-body grid for the core stage has moved.

IV. Results

Fully viscous solutions were computed for both the SRB separation and the LPVD simulations. For each simulation case, a steady-state solution was first computed until the aerodynamic coefficients stabilized. Then the solution and grid file was copied into a new working directory that contained all of the input files required for the dynamic simulation and the *restart* feature in OVERFLOW was activated.

A. Half-Configuration of SRB Separation

A steady-state solution was computed for the half-configuration SRB separation case. First a subsonic case was completed to ensure all OVERFLOW input parameters were selected correctly. When a supersonic case was first assembled and computed, the solution diverged. Thus, a smoothing parameter in the *overflow.inp* namelist file named *DELTA* was changed from the default value of 1.0 to 7.0. Figure 9(a) shows the subsonic solution at the plane of symmetry for the steady-state case. Figure 9(b) shows the solution at the desired Mach number of 3.877.

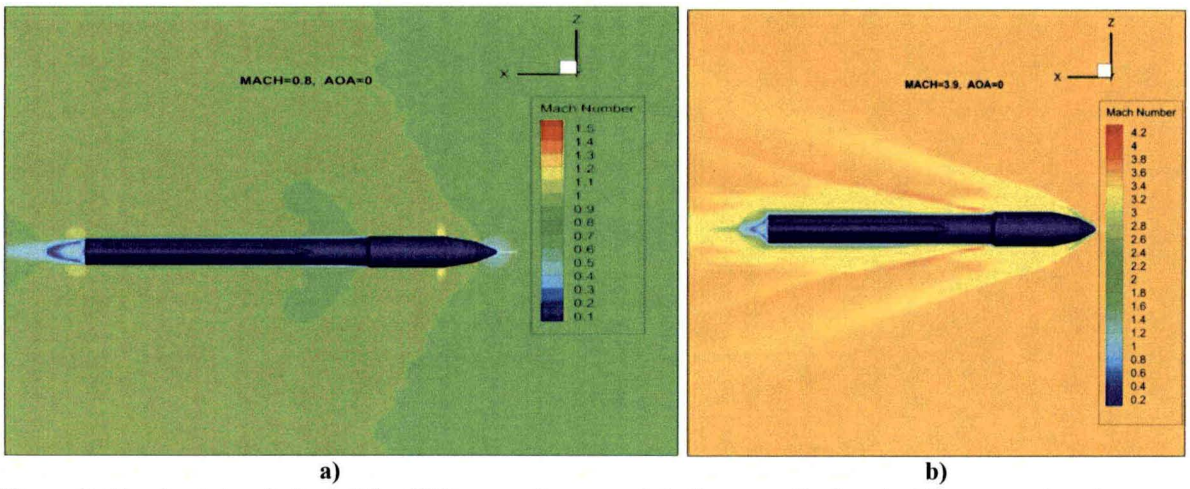


Figure 9. Steady-state solution of the SRB separation case. Solutions are displayed at the symmetry plane. a) $M_\infty = 0.8$, $\alpha = 0.0°$ b) $M_\infty = 3.877$, $\alpha = 0.0°$

Interpolation error was evident in the wake region of the core in figure 9(b). This error was attributed to the difference in cell size form the core's near-body grid and the nearest off-body grid. The near-body grid of the core shows a Mach number of about 3.2 and then an abrupt increase to about 3.6.

With a time-step of 0.001 second, the simulation was allowed to run for a total of 5000 iterations which simulated 5 seconds. Figure 10 shows the predicted grid motion of the right SRB. Figure 11 shows the coordinate values of the SRB CM in all three dimensions. The relative orientation of the coordinates axes to the vehicle is also shown in figure 11. The applied ejection forces and moment (table 2) were applied to CM from 0.0 to 0.75 seconds[3].

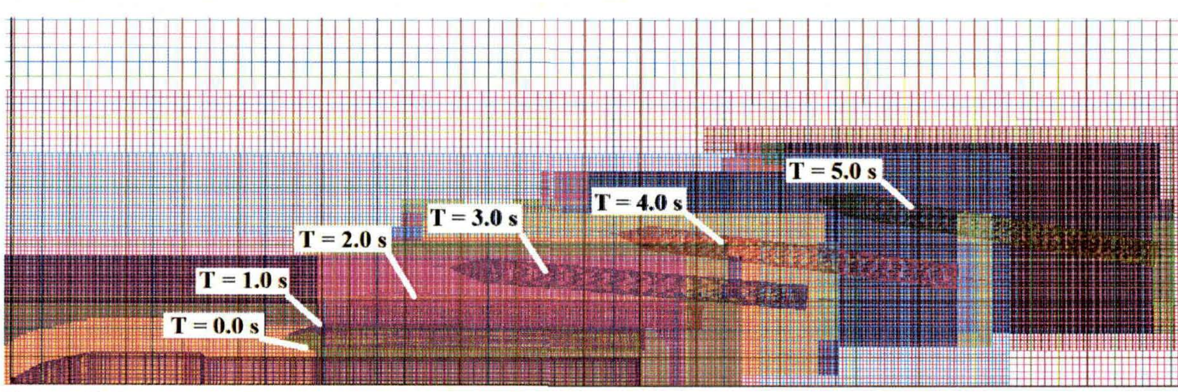


Figure 10. Top view of near- and off-body grids in one second intervals during aerodynamic 6-DOF motion. $M_\infty = 3.877$, $\alpha = 3.0°$, $\gamma = 36.996°$, $Re_\infty = 18{,}370.77$, $\beta = 0.0°$

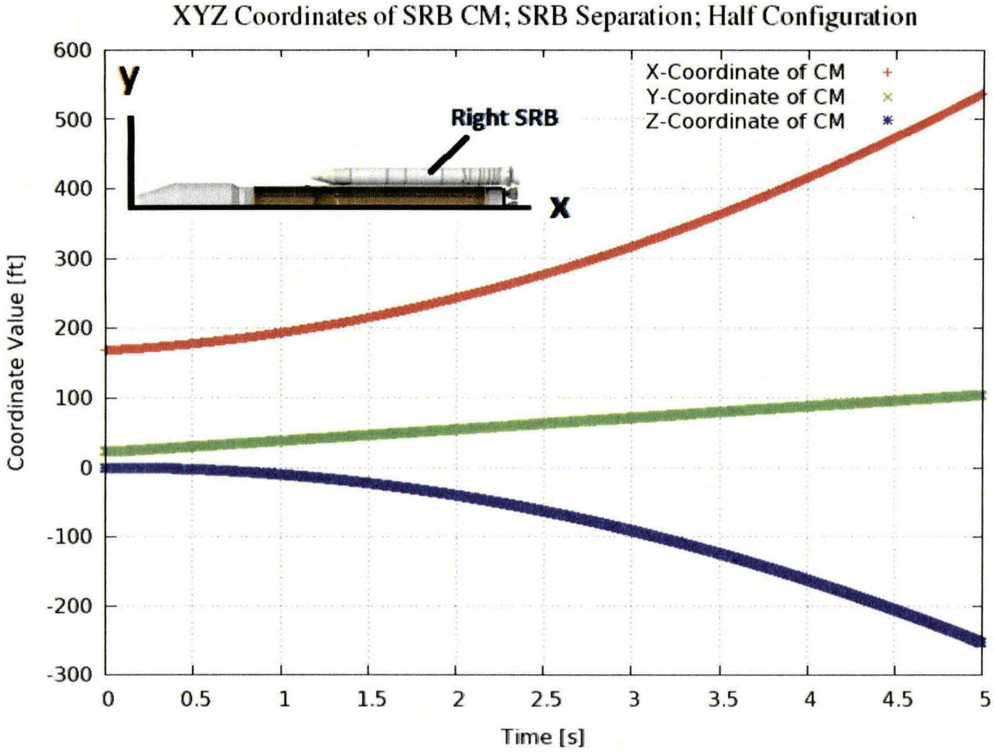


Figure 11. Plot of the SRB CM in the x, y, and z directions during SRB separation for the half-configuration. $\Delta t = 0.001s$, $M_\infty = 3.877$, $\alpha = 3.0°$, $\gamma = 36.996°$, $Re_\infty = 18{,}370.77$, $\beta = 0.0°$

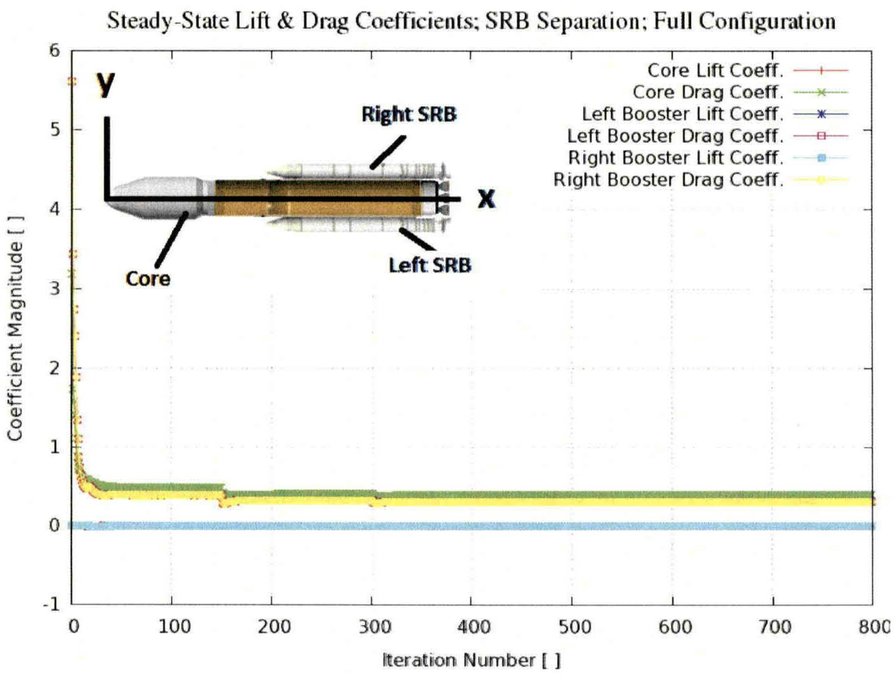


Figure 12. Convergence of steady-state lift and drag coefficients for the full-configuration of the SRB separation case.

B. Full-Configuration of SRB Separation

Once all issues were resolved in the half-configuration case for the SRB separation, a full simulation was assembled. Figure 12 (page 9) shows the convergence of the aerodynamic coefficients for the steady-state case. Due to the larger size of the grid file, the 6-DOF solution calculation was proceeding at an exceedingly slow rate of 1,000 iterations every 2 days on 4 processors. A 100 processor computation was then submitted to the NASA Columbia Server at Ames Research Center. The computational time was significantly reduced to about 20 minutes for 1,000 iterations.

C. LPVD Simulation in 3-DOF

The first simulation created for the LPVD was a 3-DOF case. The simulation results predicted an unfavorable motion as shown in figure 13. The motion was attributed to the low principal moment of inertia about the y-axis that was selected (see table 3). This simulation could be considered to be a rocket that launches form a launch pad without control systems.

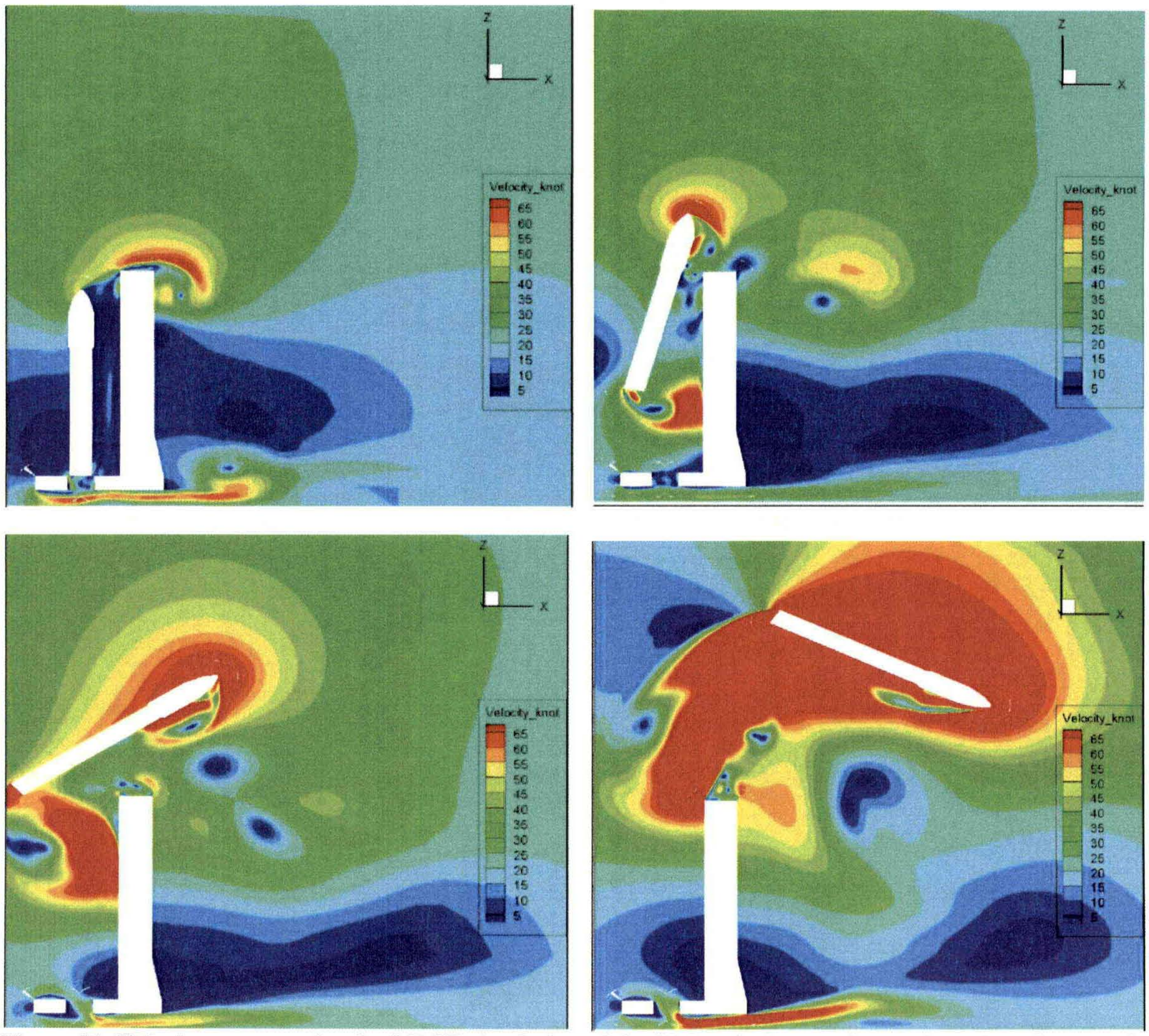
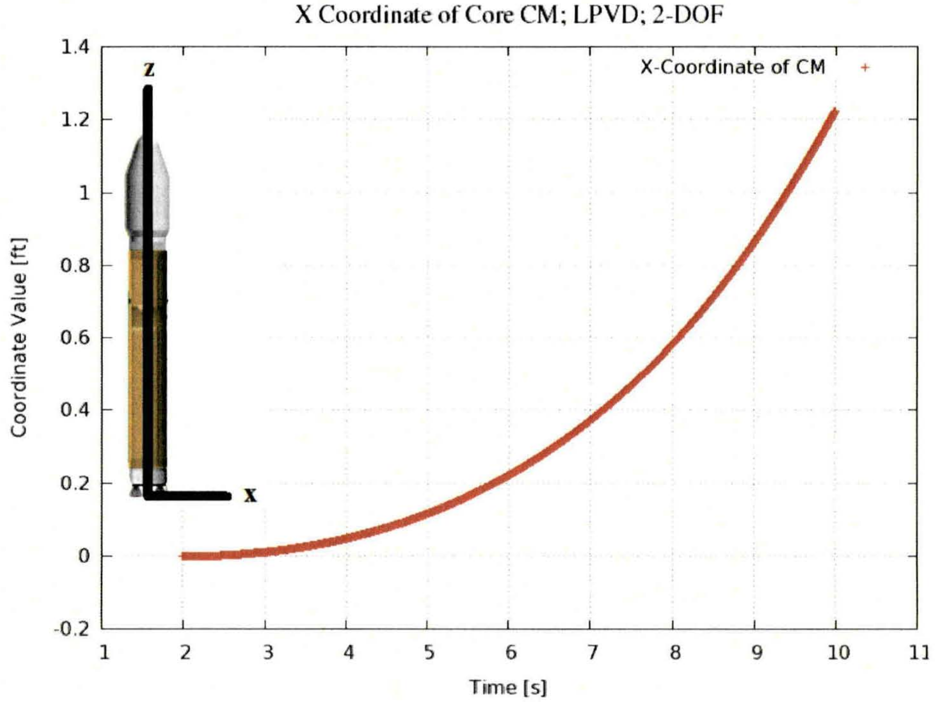


Figure 13. Velocity contours for the 3-DOF simulation of the SLS as it departs from a launch pad. A steady 20 knot crosswind flows from left to right. Time is increasing from left to right then top to bottom. The motion was not expected.

D. LPVD Simulation in 2-DOF

Once the unexpected motion was viewed in the 3-DOF case, the *Scenario.xml* file was modified to constrain the rotation so that only 2-DOF remained (see appendix D, figure D4). As shown in figure 14, the predicted motion

seemed reasonable. The core stage drifted about 1.2 feet in the direction of the tower following 8 seconds of flight time. The thrust was not activated until 2 seconds of simulation time. The time step for this simulation was 0.001 second. Figure 15 shows the flow solution for the 2-DOF case.



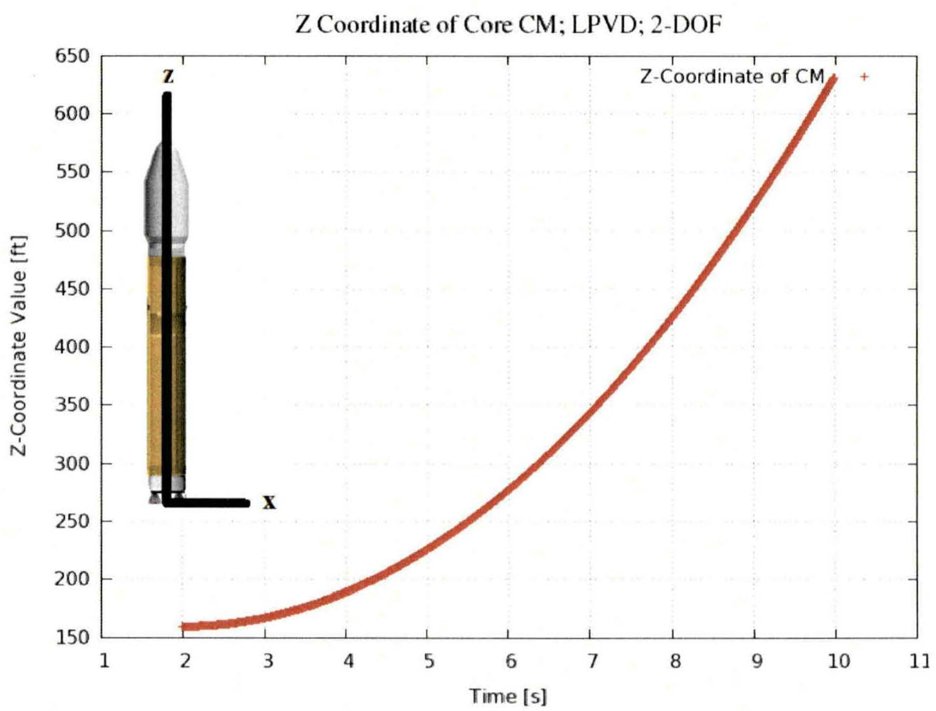


Figure 14. X and Z coordinates of launch vehicle CM for the 2-DOF case. Thrust was activated after 2 seconds of simulation time. (Note that the highest point on the launch tower was 351 feet. (See appendix A; figure A2)

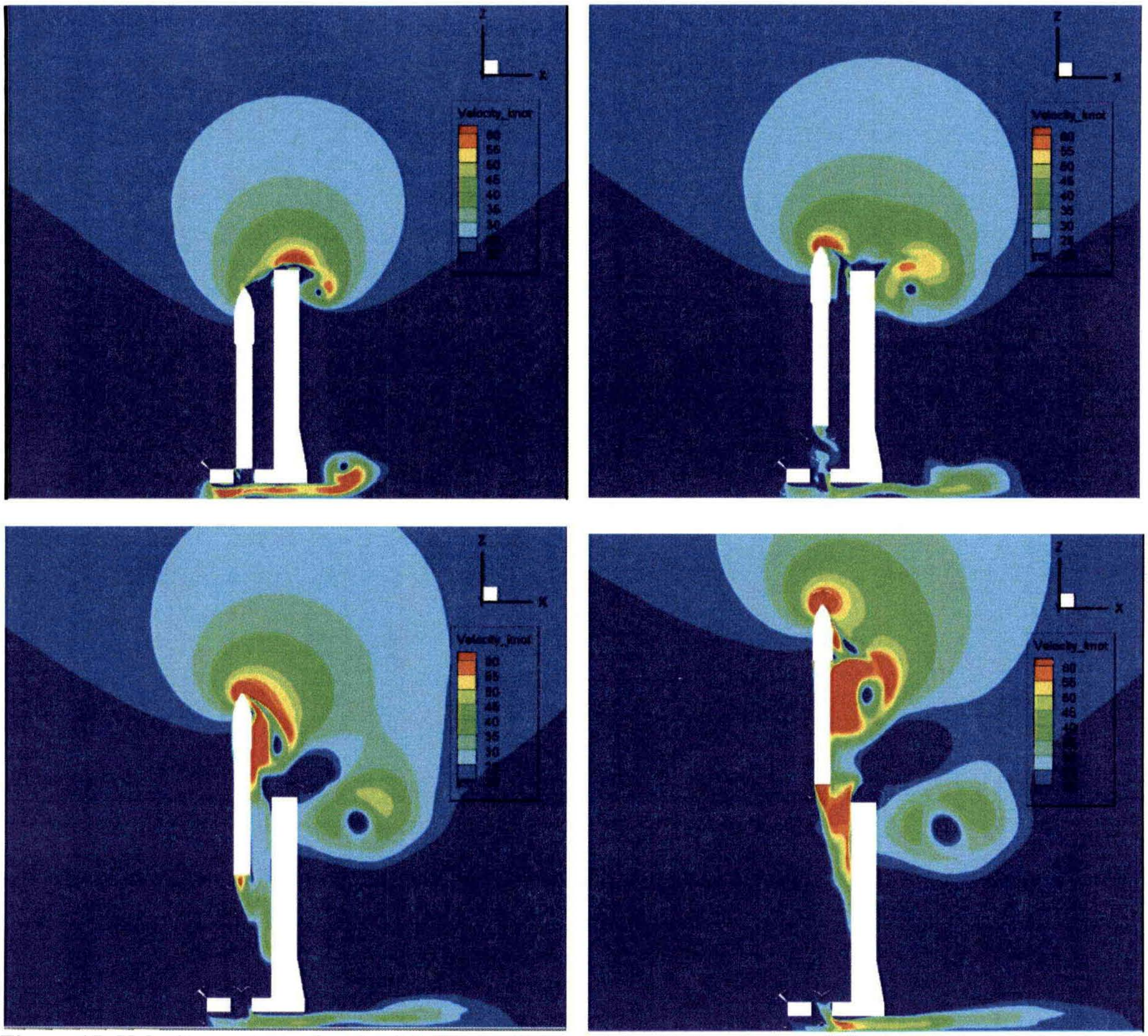


Figure 15. Velocity contours for the 2-DOF simulation of the SLS as it departs from a launch pad. A steady 20 knot crosswind flows from left to right. Time is increasing from left to right then top to bottom.

V. Concluding Remarks

NE-M1 has not had the capability to simulate RBD with interactions from accurate aerodynamic load models. During the course of this project, two simulations were prepared in OVERFLOW-D to demonstrate the influence of aerodynamic loads on rigid bodies in motion. Since a SLS is being considered by NASA, the geometry for the simulations were based on conceptual SLS designs.

A fully 3D model with 6-DOF was developed to simulate the dynamical motion of SRBs as they separate from the core stage. Although the accuracy of the simulations were not verified, a template that contains lessons learned from using 6-DOF motion in OVERFLOW-D can be created so that future users can avoid issues encountered in this project.

LPVD of the conceptual SLS was also simulated in 2D by allowing 2-DOF and 3-DOF. Since the objective of the project was for demonstrational purposes, the decision to reduce the simulation to 2D allowed for rapid preparation and computation of the simulation.

The inertial properties employed in these simulations were not accurate; however, NE-M1 can now begin to approach more detailed CFD analyses that involve RBD. In the future, Guidance, Navigation, and Control experts should be consulted for an accurate description of the ejection loads that should be applied to the SRBs.

Appendix

A. File contents of *origin.dat* and *12pts.dat*

```
1 1 1
0.0 0.0 0.0
```

Figure A1. PLOT3D formatted file named *origin.dat* for use in OVERGRID to create a single point at the origin.

```
          12
    1         1         1
    1         1         1
    1         1         1
    1         1         1
    1         1         1
    1         1         1
    1         1         1
    1         1         1
    1         1         1
    1         1         1
    1         1         1
    1         1         1
-56.0000000E+00  0.0000000E+00  0.0000000E+00
-16.750000000E+00  0.0000000E+00  0.0000000E+00
-16.750000000E+00  0.0000000E+00  -24.0000000E+00
16.750000000E+00  0.0000000E+00  -24.0000000E+00
16.750000000E+00  0.0000000E+00  0.0000000E+00
47.750000000E+00  0.0000000E+00  0.0000000E+00
47.750000000E+00  0.0000000E+00  351.0000000E+00
89.750000000E+00  0.0000000E+00  351.0000000E+00
89.750000000E+00  0.0000000E+00  75.0000000E+00
102.00000000E+00  0.0000000E+00  0.0000000E+00
102.00000000E+00  0.0000000E+00  -24.0000000E+00
-56.0000000E+00  0.0000000E+00  -24.0000000E+00
```

Figure A2. PLOT3D formatted file made for use in OVERGRID to create 2D launch pad model. (each line of text that has multiple significant figures are the x, y, and z coordinates of the corners in feet.)

B. OVERFLOW-D Input Files for Half-Configuration of the SRB Separation Case

```
$GLOBAL
   RESTRT = .T.,  NSTEPS = 5000, NFOMO = 1, NSAVE = 1000,
   NQT = 102,  NQC = 0,
   TPHYS = 0,  DTPHYS= 4.112,
   MULTIG = .T., FMG = .F., FMGCYC = 150,150,
   $END

$OMIGLB
   IRUN = 0,
   I6DOF = 2, DYNMCS = .T., NADAPT = -200,
   $END

$DCFGLB
   DQUAL = 1.0, NORFAN = 0,
   $END

$GBRICK
   OBGRIDS = .T.,
   DFAR = 3000,  DS = 0.9,
   XNCEN = 160,  YNCEN = 0.0,  ZNCEN = 0.0,
   I_YMIN = 1, P_YMIN = 0.0, MINBUF = 4,
   $END

$BRKINP
   NBRICK = 0,
   $END

$GROUPS
   $END

$XRINFO IDXRAY= 1,  IGXLIST= 2,  XDELTA = 1.25, $END
$XRINFO IDXRAY= 2,  IGXLIST= 1,  XDELTA = 1.25, $END
$XRINFO IDXRAY= 1,  IGXLIST= -1,  XDELTA = 17, $END
$XRINFO IDXRAY= 2,  IGXLIST= -1,  XDELTA = 6, $END


$FLOINP
   FSMACH = 3.877,  REFMACH = 3.877,  ALPHA = 3.0,
   REY = 18370.77,  TINF = 468.2408,
   $END

$VARGAM $END


$GRDNAM
   NAME = 'main',
   $END

$NITERS $END
$METPRM
   IRHS = 6,  ILHS = 6,  IDISS = 3,
   BIMIN = 1.0,
   $END

$TIMACU
   ITIME = 0,  CFLMIN = 5.0,  CFLMAX = 0.0,
   $END

$SMOACU
   ISPEC = 2,  SMOO = 1.0,  DIS2 = 2.0,  DIS4 = 0.04,
   DELTA = 7,
   $END

$VISINP
   VISC = .T.,
   $END

$BCINP
   IBTYP =    5,  15,  15,  17,  17,
   IBDIR =    3,   1,  -1,   2,  -2,
   JBCS  =    1,   1,  -1,   1,   1,
   JBCE  =   -1,   1,  -1,  -1,  -1,
   KBCS  =    1,   1,   1,   1,  -1,
   KBCE  =   -1,  -1,  -1,   1,  -1,
   LBCS  =    1,   1,   1,   1,   1,
   LBCE  =    1,  -1,  -1,  -1,  -1,
   $END

$SCEINP $END

$GRDNAM
   NAME = 'booster',
   $END

$NITERS $END

$METPRM
   $END

$TIMACU
   $END

$SMOACU
   $END

$VISINP
   VISC = .T.,
$BCINP
   IBTYP =    5,  15,  15,  10,
   IBDIR =    3,   1,  -1,   2,
   JBCS  =    1,   1,  -1,   1,
   JBCE  =   -1,   1,  -1,  -1,
   KBCS  =    1,   1,   1,   1,
   KBCE  =   -1,  -1,  -1,   1,
   LBCS  =    1,   1,   1,   1,
   LBCE  =    1,  -1,  -1,  -1,
   $END

$SCEINP $END


$GRDNAM
   NAME = 'Off-body grids',
   $END

$NITERS $END

$METPRM
   $END

$TIMACU
   $END

$SMOACU
   $END

$VISINP
   VISC = .T.,
   $END

$BCINP
   $END

$SCEINP $END
```

Figure B1. Overflow.inp for half-configuration of the SRB separation case.

```xml
<?xml version='1.0' encoding='utf-8'?>
<Configuration AngleUnit="degree">

   <Component Name="main" Type="struc">
      <Data> Grid List=1 </Data>
   </Component>

   <Component Name="booster" Type="struc">
      <Data> Grid List=2 </Data>
   </Component>

</Configuration>
```

Figure B2. Config.xml file for half-configuration of the SRB separation case.

```xml
<?xml version='1.0' encoding='utf-8'?>
<Scenario AngleUnit="degree" Gravity="1.43441E-6,0.0,-1.20217E-6">

<Aero6dof Component="booster" Start="0.0" Duration="0.0">
   <InertialProperties
      Mass="3.7763e+09"
      CenterOfMass="169.4845, 23.4667, 0.0"
      PrincipalMomentsOfInertia="143191840543.0, 7510971307750.0, 7522448851710.0" >
      <PrincipalAxesOrientation Axis="-0.999999977151, -9.45999818456e-5, 0.00019169779858" Angle="0.0"/>
   </InertialProperties>
   <AppliedLoad
   Start="0.0" Duration="750" Frame="body" Force="1.6e4, 2.0e4, 0.0" Moment="0.0, 0.0, -1.0E5"
   </AppliedLoad>
</Aero6dof>

</Scenario>
```

Figure B3. Scenario.xml file for half-configuration of the SRB separation case.

```
0, 500, 500, -1, 0, 0                    FSMACH,ALPHA,BETA,REY,GAMINF,TINF
2                                        NREF
33, 855.3, 160, 0., 0.                   REFL,REFA,XMC,YMC,ZMC
12.2, 116.9, 169.4845, 23.4667, 0.0  REFL,REFA,XMC,YMC,ZMC
2                                        NSURF


1, 1                                     NSUB,IREFS
1, 3, 1,-1,  1,  -1,  1,  1              NG,IBDIR,JS,JE,KS,KE,LS,LE
0                                        NPRI

1, 2                                     NSUB,IREFS
2, 3, 1,-1,  1,  -1,  1,  1              NG,IBDIR,JS,JE,KS,KE,LS,LE
0                                        NPRI


2                                        NCOMP

main
1, 1                                     NIS,IREFC
1                                        (surface numbers)

booster
1, 2                                     NIS,IREFC
2                                        (surface numbers)
```

Figure B4. Mixsur.inp file for half-configuration of the SRB separation case.

C. OVERFLOW-D Input Files for Full-Configuration of the SRB Separation Case

```
$GLOBAL
   RESTRT = .T.,  NSTEPS = 5000, NFOMO = 1, NSAVE = 1000,
   NQT = 102,  NQC = 0,
   TPHYS = 0,  DTPHYS= 4.112,
   MULTIG = .T., FMG = .F., FMGCYC = 150,150,
   $END

$OMIGLB
   IRUN = 0,
   I6DOF = 2, DYNMCS = .T., NADAPT = -200,
   $END

$DCFGLB
   DQUAL = 1.0, NORFAN = 0,
   $END

$GBRICK
   OBGRIDS = .T.,
   DFAR = 3000,  DS = 0.9,
   XNCEN = 160,  YNCEN = 0.0,  ZNCEN = 0.0,
   $END

$BRKINP
   NBRICK = 0,
   $END

$GROUPS
   $END

$XRINFO IDXRAY= 1,  IGXLIST= 2,3  XDELTA = 1.25, $END
$XRINFO IDXRAY= 2,  IGXLIST= 1,  XDELTA = 1.25, $END
$XRINFO IDXRAY= 1,  IGXLIST= -1,  XDELTA = 17, $END
$XRINFO IDXRAY= 2,  IGXLIST= -1,  XDELTA = 6, $END
$XRINFO IDXRAY= 3,  IGXLIST= -1,  XDELTA = 6, $END
$XRINFO IDXRAY= 3,  IGXLIST= 1,  XDELTA = 1.25, $END


$FLOINP
   FSMACH = 3.877,  REFMACH = 3.877,  ALPHA = 0.0,
   REY = 18370.77,  TINF = 468.2408,
   $END

$VARGAM $END


$GRDNAM
   NAME = 'main',
   $END
```

```
$NITERS $END

$METPRM
   IRHS = 6,  ILHS = 6,  IDISS = 3,
   BIMIN = 1.0,
   $END

$TIMACU
   ITIME = 0,  CFLMIN = 5.0,  CFLMAX = 0.0,
   $END

$SMOACU
   ISPEC = 2,  SMOO = 1.0,  DIS2 = 2.0,  DIS4 = 0.04,
   DELTA = 7,
   $END

$VISINP
   VISC = .T.,
   $END

$BCINP
   IBTYP =    5,  15,  15,  10,
   IBDIR =    3,   1,  -1,   2,
   JBCS  =    1,   1,  -1,   1,
   JBCE  =   -1,   1,  -1,  -1,
   KBCS  =    1,   1,   1,   1,
   KBCE  =   -1,  -1,  -1,   1,
   LBCS  =    1,   1,   1,   1,
   LBCE  =    1,  -1,  -1,  -1,
   $END
$SCEINP $END


$GRDNAM
   NAME = 'Rbooster',
   $END

$NITERS $END

$METPRM
   $END

$TIMACU
   $END

$SMOACU
   $END
```

```
$VISINP
   VISC = .T.,
   $END

$BCINP
   IBTYP =    5,  15,  15,  10,
   IBDIR =    3,   1,  -1,   2,
   JBCS  =    1,   1,  -1,   1,
   JBCE  =   -1,   1,  -1,  -1,
   KBCS  =    1,   1,   1,   1,
   KBCE  =   -1,  -1,  -1,   1,
   LBCS  =    1,   1,   1,   1,
   LBCE  =    1,  -1,  -1,  -1,
   $END

$SCEINP $END

$GRDNAM
   NAME = 'Lbooster',
   $END

$NITERS $END

$METPRM
   $END

$TIMACU
   $END

$SMOACU
   $END

$VISINP
   VISC = .T.,
   $END

$BCINP
   IBTYP =    5,  15,  15,  10,
   IBDIR =    3,   1,  -1,   2,
   JBCS  =    1,   1,  -1,   1,
   JBCE  =   -1,   1,  -1,  -1,
   KBCS  =    1,   1,   1,   1,
   KBCE  =   -1,  -1,  -1,   1,
   LBCS  =    1,   1,   1,   1,
   LBCE  =    1,  -1,  -1,  -1,
   $END

$SCEINP $END
```

```
$GRDNAM
   NAME = 'Off-body grids',
   $END

$NITERS $END

$METPRM
   $END

$TIMACU
   $END

$SMOACU
   $END

$VISINP
   VISC = .T.,
   $END

$BCINP
   $END

$SCEINP $END
```

Figure C1. Overflow.inp file for full-configuration of the SRB separation case.

```
<?xml version='1.0' encoding='utf-8'?>
<Configuration AngleUnit="degree">

   <Component Name="main" Type="struc">
      <Data> Grid List=1 </Data>
   </Component>

   <Component Name="Rbooster" Type="struc">
      <Data> Grid List=2 </Data>
   </Component>

   <Component Name="Lbooster" Type="struc">
      <Data> Grid List=3 </Data>
      <Transform>
        <Translate Displacement="0.0, -46.9338, 0.0" />
      </Transform>
   </Component>

</Configuration>
```

Figure C2. Config.xml file for full-configuration of the SRB separation case.

```
<?xml version='1.0' encoding='utf-8'?>
<Scenario AngleUnit="degree" Gravity="1.43441E-6,0.0,-1.20217E-6">

<Aero6dof Component="Rbooster" Start="0.0" Duration="0.0">
   <InertialProperties
      Mass="3.7763e+09"
      CenterOfMass="169.4845, 23.4667, 0.0"
      PrincipalMomentsOfInertia="143191840543.0, 7510971307750.0, 7522448851710.0" >
      <PrincipalAxesOrientation Axis="-0.999999977151, -9.45999818456e-5, 0.00019169779858" Angle="0.0"/>
   </InertialProperties>
   <AppliedLoad
   Start="0.0" Duration="750" Frame="body" Force="1.6e4, 2.0e4, 0.0" Moment="0.0, 0.0, -1.0E5"
   </AppliedLoad>
</Aero6dof>

<Aero6dof Component="Lbooster" Start="0.0" Duration="0.0">
   <InertialProperties
      Mass="3.7763e+09"
      CenterOfMass="169.4845, -23.4667, 0.0"
      PrincipalMomentsOfInertia="143191840543.0, 7510971307750.0, 7522448851710.0" >
      <PrincipalAxesOrientation Axis="-0.999999977151, -9.45999818456e-5, 0.00019169779858" Angle="0.0"/>
   </InertialProperties>
   <AppliedLoad
   Start="0.0" Duration="750" Frame="body" Force="1.6e4, -2.0e4, 0.0" Moment="0.0, 0.0, 1.0E5"
   </AppliedLoad>
</Aero6dof>

</Scenario>
```

Figure C3. Scenario.xml file for full-configuration of the SRB separation case.

```
0, 500, 500, -1, 0, 0                  FSMACH,ALPHA,BETA,REY,GAMINF,TINF
3                                      NREF
33, 855.3, 160, 0., 0.                 REFL,REFA,XMC,YMC,ZMC
12.2, 116.9, 169.4845, 23.4667, 0.0  REFL,REFA,XMC,YMC,ZMC
12.2, 116.9, 169.4845, 23.4667, 0.0  REFL,REFA,XMC,YMC,ZMC
3                                      NSURF

1, 1                                   NSUB,IREFS
1, 3, 1,-1,  1,  -1,  1,  1            NG,IBDIR,JS,JE,KS,KE,LS,LE
0                                      NPRI

1, 2                                   NSUB,IREFS
2, 3, 1,-1,  1,  -1,  1,  1            NG,IBDIR,JS,JE,KS,KE,LS,LE
0                                      NPRI

1, 3                                   NSUB,IREFS
2, 3, 1,-1,  1,  -1,  1,  1            NG,IBDIR,JS,JE,KS,KE,LS,LE
0                                      NPRI

3                                      NCOMP

main
1, 1                                   NIS,IREFC
1                                      (surface numbers)

Rbooster
1, 2                                   NIS,IREFC
2                                      (surface numbers)

Lbooster
1, 3                                   NIS,IREFC
3                                      (surface numbers)
```

Figure C4. Mixsur.inp file for full-configuration of the SRB separation case.

D. OVERFLOW-D Input Files for the LPVD Case

```
$GLOBAL
   RESTRT = .T.,  NSTEPS = 8000, NFOMO = 1, NSAVE = 200,
   NQT = 102,  NQC = 0,
   DTPHYS = 0.033756197,  FSONWT = 2, NITNWT = 2,
   $END

$OMIGLB
   IRUN = 0,  IBYMIN= 21, IBYMAX= 21,
   LFRINGE = 2, NADAPT = -50,
   DYNMCS = .T.,  I6DOF = 2,
   $END

$DCFGLB
   DQUAL = 1.0,  MORFAN = 0,  NORFAN = 0,
   $END


$GBRICK
   OBGRIDS = .T.,
   DFAR = 3000,  DS = 2,
   XNCEN = 0,  YNCEN = 0,  ZNCEN = 166,
   I_ZMIN = 1, P_ZMIN = -51, MINBUF = 6
   $END

$BRKINP    $END

$GROUPS    $END

$XRINFO IDXRAY = 1, IGXLIST = 2,3, XDELTA = 1 $END
$XRINFO IDXRAY = 1, IGXLIST = -1, XDELTA = 19 $END
$XRINFO IDXRAY = 2, IGXLIST = 1, XDELTA = 1 $END
$XRINFO IDXRAY = 2, IGXLIST = -1, XDELTA = 16 $END


$FLOINP
   FSMACH = 0.0302,  REFMACH = 0.0302,
   REY = 1.41E5,  TINF = 518.7,
   $END

$VARGAM $END


$GRDNAM
   NAME = 'core',
   $END

$NITERS $END

$METPRM
```

```
$METPRM
   IRHS = 6,  ILHS = 6,  IDISS = 3,
   BIMIN = 1.0,
   $END

$TIMACU
   ITIME = 0,
   TFOSO = 2,
   $END

$SMOACU
   ISPEC = 2,  SMOO = 1.0,  DIS2 = 2.0,  DIS4 = 0.04,
   FSO = 2.0,  DELTA = 1.0,
   $END

$VISINP
   VISC = .T.,
   $END

$BCINP
   IBTYP =    5,  21,  10,
   IBDIR =    3,   2,   1,
   JBCS  =    1,   1,   1,
   JBCE  =   -1,  -1,   1,
   KBCS  =    1,   1,   1,
   KBCE  =   -1,   1,  -1,
   LBCS  =    1,   1,   1,
   LBCE  =    1,  -1,  -1,
   $END

$SCEINP $END


$SIXINP $END
$GRDNAM
   NAME = 'Lpad',
   $END

$NITERS $END
$METPRM $END
$TIMACU $END
$SMOACU $END

$VISINP
   VISC = .T.,
   $END
```

```
$BCINP
   IBTYP =    5,  21,  10,
   IBDIR =    3,   2,   1,
   JBCS  =    1,   1,   1,
   JBCE  =   -1,  -1,   1,
   KBCS  =    1,   1,   1,
   KBCE  =   -1,   1,  -1,
   LBCS  =    1,   1,   1,
   LBCE  =    1,  -1,  -1,
   $END

$SCEINP $END


$SIXINP $END
$GRDNAM
   NAME = 'Rpad',
   $END

$NITERS $END
$METPRM $END
$TIMACU $END
$SMOACU $END

$VISINP
   VISC = .T.,
   $END

$BCINP
   IBTYP =    5,  21,  10,
   IBDIR =    3,   2,   1,
   JBCS  =    1,   1,   1,
   JBCE  =   -1,  -1,   1,
   KBCS  =    1,   1,   1,
   KBCE  =   -1,   1,  -1,
   LBCS  =    1,   1,   1,
   LBCE  =    1,  -1,  -1,
   $END
$SCEINP $END


$SIXINP $END
$GRDNAM
   NAME = 'Off-body grids',
   $END

$NITERS $END
$METPRM $END
$TIMACU $END
$SMOACU $END

$VISINP
   VISC = .T., $END

$BCINP $END
$SCEINP $END
```

Figure D1. Overflow.inp file for both 2-DOF and 3-DOF LPVD case.

```
<?xml version='1.0' encoding='utf-8'?>
<Configuration AngleUnit="radian">

   <Component Name="core" Type="struc">
      <Data> Grid List=1 </Data>
   </Component>

   <Component Name="pad" Type="struc">
      <Data> Grid List=2, 3 </Data>
   </Component>

</Configuration>
```

Figure D2. Config.xml file for both 2-DOF and 3-DOF LPVD case.

```
<?xml version='1.0' encoding='utf-8'?>
<Scenario AngleUnit="radian" Gravity="0.0, 0.0, -0.02823566">

<Aero6dof Component="core" Start="0" Duration="0">
   <InertialProperties
      Mass="7.53E7"
      CenterOfMass="0, 0, 160"
      PrincipalMomentsOfInertia="0.0, 7E7, 0.0" >
      <PrincipalAxesOrientation Axis="1.0, 0.0, 0.0" Angle="0.0"/>
   </InertialProperties>
   <AppliedLoad
   Start="0.0"  Frame="body" Force="0.0, 0.0, 3.1E6" Moment="0.0, 0.0, 0.0"
   </AppliedLoad>
</Aero6dof>

</Scenario>
```

Figure D3. Scenario.xml file for 3-DOF LPVD case.

```
<?xml version='1.0' encoding='utf-8'?>
<Scenario AngleUnit="radian" Gravity="0,0,-0.0282357">

<Aero6dof Component="core" Start="0 " >
   <InertialProperties
      Mass="7.53E7"
      CenterOfMass="0, 0, 160"
      PrincipalMomentsOfInertia="0.0, 7E7, 0.0" >
      <PrincipalAxesOrientation Axis="1.0, 0.0, 0.0" Angle="0.0"/>
   </InertialProperties>
   <AppliedLoad Start="0.0 " Duration=" 0.0 " Frame="body"
                Force=" 0.0 ,  0.0 ,  3.1E6 " Moment=" 0.0 ,  0.0 ,  0.0" />
   <Constraint Start="0.0" Duration="0.0" Translate="0, 0, 0" Rotate="0, 1, 0" />
</Aero6dof>

</Scenario>
```

Figure D4. Scenario.xml file for 2-DOF LPVD case.

```
0, 500, 500, -1, 0, 0    FSMACH,ALPHA,BETA,REY,GAMINF,TINF
1                        NREF
33, 10378.5, 0.0, 0.0, 160.       REFL,REFA,XMC,YMC,ZMC
1                        NSURF


1, 1                       NSUB (core),IREFS
1, 3,  1, -1,  1,  -1,  1, 1         NG,IBDIR,JS,JE,KS,KE,LS,LE
0                                    NPRI


1                        NCOMP

core
1, 1                       NIS,IREFC
1                          (surface numbers)
```

Figure D5. Mixsur.inp file for both 2-DOF and 3-DOF LPVD case.

Acknowledgments

I would like to thank the Undergraduate Student Research Program for organizing an excellent internship program. USRP has allowed me to develop skills that I have yet to encounter in my undergraduate studies. I thank all the USRP personnel for letting me have the privilege to acquire skills and experiences that are pertinent to my field of study. I thank Bruce Vu and Douglas Willard at NASA KSC for taking time out of their busy work-schedules to mentor me and for supporting my needs for guidance in such an early and important part of my career. I would like to thank Leonard Duncil in the Launch Services Program for allowing me to have access to his computing resources, and for sharing his knowledge on the NASA OVERFLOW flow solver.

References

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